JARQ 45 (1), 69 - 76 (2011) http://www.jircas.affrc.go.jp

REVIEW

Food Processing and Cooking with New Heating System Combining Superheated Steam and Hot Water Spray

Itaru SOTOME* and Seiichiro ISOBE

National Food Research Institute, National Agriculture and Food Research Organization (Tsukuba, Ibaraki 305-8642, Japan)

Abstract

Superheated steam (SHS) was applied to food processing because of advantages including efficient heat transfer by latent heat, and prevention of product oxidation. SHS heating solves problems such as water absorption and dissolution of solid content from foods caused by hot water or saturated steam heating; however, it causes low product yield due to its high drying capacity. To fix these problems, a new system using SHS around 115°C and a spray of hot water micro droplets (WMD) has been developed. The SHS+WMD system has simultaneously improved the quality and yield of blanched potatoes and other vegetables. In addition, it was found that WMD increased the heat transfer efficiency of SHS. This was presumably because WMD reduced the thermal resistance of the condensed water layer on the product surface by stirring the condensate. Due to this effect, the required time for the surface pasteurization of some kinds of raw vegetables decreased. A standard plate count of bacterium on cucumber fruit decreased from 10^5 CFU/g to 300 CFU/g with a slight texture change by SHS+WMD heating for 30 s. The SHS+WMD system is currently used in the food industry for cooking potato salad, and preprocessing meat, as well as the pasteurization of fishery products in Japan.

Discipline: Food

Additional key words: blanching, cucumber fruit, potato, surface pasteurization

Introduction

Superheated steam (SHS) is steam at a temperature higher than the boiling point of water. SHS has been used for more than 100 years as a power source, as well as a heating medium for drying chemicals and timber. SHS has also been applied to many kinds of food processing[59]. A report on food processing with SHS appeared in the 1950s[7]. The advantages of SHS heating in food processing include efficient heat transfer by latent heat and gas radiation, as well as prevention of nutrient oxidation in food. In SHS heating, steam condensation followed by condensate evaporation was observed. These features of SHS enabled high-efficiency heating and the drying of food materials; therefore, the kinetics of heat and moisture transfer between SHS and food materials have been reported in detail[8,9,10,15,16,18,55]. In addition, food materials are usually surrounded by steam and not exposed to air during SHS heating; as a result, the food materials during SHS heating are prevented from oxidizing. It has been reported that SHS is an efficient means of preventing oil oxidation and preserving some nutritional components during heating[3,5,12,13]. Food processing with SHS is still under study, and SHS has been applied to blanching or steaming[2,5,9,18,22], pasteurization[1,7,11,19,25,32,33,39], extraction[41], decontamination of mycotoxins[6,38], and other food processing[21,42]. SHS has also been applied to drying potatoes[14], bananas[24], noodles[26], chicken meat[28], shrimp[29], scallops[31], soybeans[37], rice[40,43,49,50], sugar beet pulp[52], spent grain[53,54], and other products[60,62]. In recent years, low-pressure SHS drying, which is expected to improve the quality of a product and energy efficiency, has been applied to spices and herbs[4,20], potato chips[17,23,36], and other products[27,30].

Drying capacity is one of the advantages of SHS; however, difficulties can arise when applying this technology to the cooking and blanching of fruits and vegetables. As the drying rate of the food product depends on heat flow (e.g., convection and radiation heat transfers from SHS) into the product, it is usually difficult to simultaneously achieve optimum product moisture content, heating time, and temperature. It is expected that the development of technology that can control the moisture content of food during SHS heating will result in increasing SHS application flexibility in food processing.

*Corresponding author: e-mail itarus@affrc.go.jp

Received 22 January 2010: accepted 21 April 2010.

To prevent food materials from drying during SHS heating, we have developed a food processing system using a combination of SHS and a spray of hot water micro droplets (WMD). In the SHS+WMD system, pressurized boiling water and steam (120 to 140°C) was sprayed under atmospheric pressure through a nozzle onto the food. The steam temperature inside the heating chamber was maintained at 115 to 120°C and water droplets were suspended in SHS. Using this system, the moisture content of food materials could be controlled through regulation of WMD. In addition, it was found that the heat transfer from SHS was enhanced by the presence of WMD [45].

In this paper, we will introduce the applications of the SHS+WMD system for blanching potatoes and the surface pasteurization of cucumber fruit. Furthermore, we will introduce recent applications of the SHS+WMD system in food industries and cooking in Japan.

Description of the SHS+WMD system

Figure 1 is a schematic drawing of the SHS+WMD generator[48]. In this system, water is pumped into a copper pipe (internal diameter 4 ~ 6 mm). The water is heated, and it boils inside the copper pipe under high pressure (0.2 to 0.4 MPa). The boiling water and steam are subsequently sprayed through a nozzle. The steam discharged through the nozzle is throttled and becomes SHS. The hot water is atomized with the nozzle and is suspended as micro droplets of hot water in SHS. The water droplets finally evaporate and absorb the heat of SHS. However, the temperature of SHS is maintained by heaters installed inside the heating chamber. The mixture of SHS and WMD is consequently maintained by spraying steam and water droplets. The pressure inside the heating chamber is almost atmospheric, since a portion of the steam fortified by the evaporation of droplets and supplied by the nozzle is exhausted through an outlet.

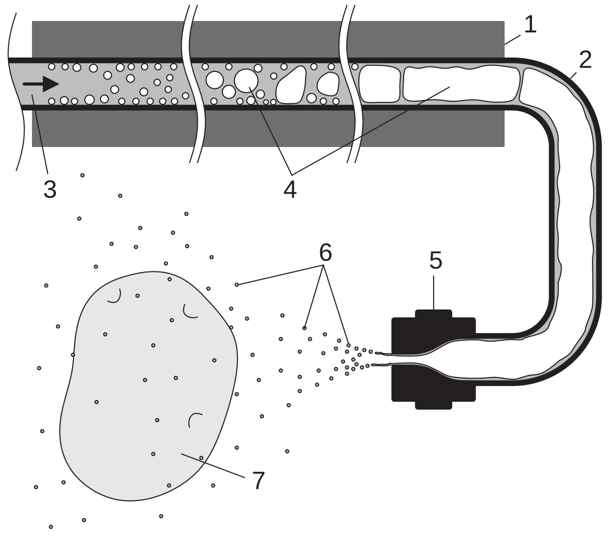

Fig. 1. Principle of superheated steam containing micro droplets of hot water (SHS+WMD)
1. Panel heater, 2. Copper pipe, 3. Hot water, 4. Steam, 5. Nozzle, 6. Micro droplets of hot water, 7. Food sample.

The water inside the copper pipe is heated by electric heaters or steam supplied by an external boiler. In a system using an electric heater, the copper pipe and heating wires are embedded in aluminum panels. The aluminum panels are installed inside the heating chamber of the system (Fig. 2). The copper pipe from the panel is connected to a manifold equipped with spray nozzles. The heaters inside the aluminum panels are also used for maintaining SHS temperature inside the heating chamber. In a system using an external boiler, the water inside the copper pipe is heated by the steam from the external boiler through a heat exchanger. Some electric heaters are installed inside the heating chamber to maintain SHS temperature.

In the SHS+WMD system, the moisture content and other attributes of the products are affected by the amount of WMD in SHS. Therefore, the WMD flow rate should be regulated appropriately for each product or for each heating purpose. The flow rates of SHS and WMD from the nozzle can be determined by measuring the internal pressure of the spray nozzle[48]. First, the total flow rate (G_{total}) of SHS and WMD is obtained from the pump setting. Second, the SHS flow rate (G_{SHS}) is given by the following equation:

$$G_{SHS} = C_d A_1 \frac{P_0}{\sqrt{RT_0}} \left(\frac{P_1}{P_0}\right)^{\frac{1}{\kappa}} \sqrt{\frac{2\kappa}{\kappa-1}\left\{1-\left(\frac{P_1}{P_0}\right)^{\frac{\kappa-1}{\kappa}}\right\}} \qquad (1)$$

where A_1 is the sectional area of the nozzle throat, P_0 and T_0 are the internal pressure and temperature of the nozzle, P_1 is the pressure at the nozzle throat, R is the specific gas constant of the steam, κ is the specific heat of the steam. In Equation 1, C_d is the discharge coefficient or nozzle coefficient. This parameter is a function of Reynolds number and must be determined by the gas flow meter before installation of the nozzle. The C_d values of the nozzle used in the SHS+WMD system were 0.90 to 0.99. When P_0 is less than 0.188 MPa, P_1 is atmospheric pressure; otherwise P_1 is given by following equation:

$$P_1 = P_0 \left(\frac{2}{\kappa+1}\right)^{\frac{\kappa}{\kappa-1}} \qquad (2)$$

Equations 1 and 2 suggest that only the nozzle internal pressure P_0 should be measured to determine G_{SHS} since T_0 is usually the saturation temperature of the water at P_0 in this

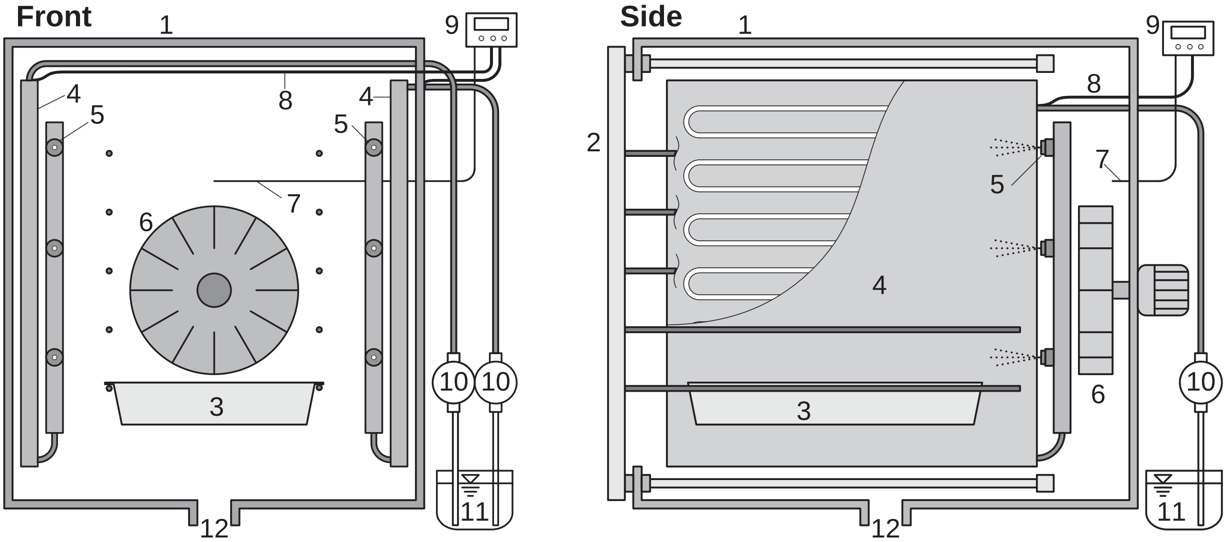

Fig. 2. Schematic drawing of the SHS+WMD system (electric heater type)
1. Chamber, 2. Door, 3. Tray or basket, 4. Heating panel, 5. Spray nozzle, 6. Fan, 7. Thermocouple, 8. Heating wire, 9. Power controller, 10. Pump, 11. Water reservoir, 12. Exhaust port.

system. Finally, the WMD flow rate G_{WMD} is obtained by $G_{WMD} = G_{total} - G_{SHS}$.

Figure 3 is a diagram of nozzle internal pressure versus WMD and SHS flow rates using an electric SHS+WMD generator. The diagram shows the steam flow rate G_{SHS}, which is calculated from the nozzle internal pressure by Equation 1. In this type of SHS+WMD generator, WMD did not discharge from the nozzle when the nozzle internal pressure was less than 0.188 MPa, and it increased as the nozzle internal pressure increased when the pressure was higher than 0.188 MPa.

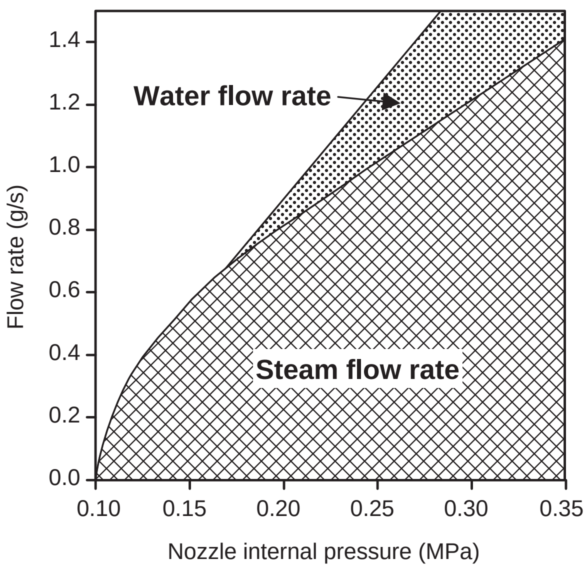

Fig. 3. Relationship between the flow rates of water and steam discharging from the spray nozzle and the internal pressure of the nozzle
The nozzle throat diameter was 1.9 mm.

Blanching potatoes [46,47,51]

For blanching potatoes, boiling water or saturated steam is usually used as a heating medium. However, softening of tissue and unexpected changes in quality are caused by water absorption into the potato tissue when these heating media are used. In addition, a portion of solid content dissolves into the hot water from the potato, especially in hot-water processing. This causes flavor loss in the potato and cost for eliminating the solid content from the water before the reuse and disposal of the water. Using SHS to blanch potatoes solves these problems. In SHS heating, steam condenses on a material, transferring a large amount of latent heat to the material in the early stage of heating. However, water condensed on the material and water inside the material evaporate after the temperature of the material increases due to the high drying capacity of SHS. Thus, water absorption is not observed in potatoes blanched with SHS. Although the drying capacity of SHS prevents water absorption into food products, it sometimes causes weight loss and the formation of a dried layer on the surface of the products due to water evaporation. To simultaneously prevent the flavor and texture changes and weight loss of potatoes that is caused by blanching, we applied the SHS+WMD system to potato blanching.

Figure 4 plots changes in the mass of the potato samples during the heating process. Potatoes weighing between 70 to 80 g were heated with SHS+WMD, SHS, and hot water. The temperature of the steam was set at 115°C in SHS+WMD and SHS heating. In hot water heating, 3.0 kg of boiling water were used. In hot water heating, the mass of the potatoes increased as the heating time increased. This was because hot water was absorbed by the potatoes. In addition, some soluble solid components were collected from the hot water used for the heating. The amount of these components was 0.15 to 0.2 g for each potato after they had been heated for more than 10 min, which was relatively large when considering the dry mass of potatoes (approximately 12 g). This dissolution of solid content would presumably decrease if the hot water were reused many times as in actual blanching. For SHS heating, the relative mass of the potatoes increased in the early stage of heating since steam condensed on the surface of the potatoes and some amount of condensed water was absorbed by the potato. However, the relative mass of the potatoes started decreasing after 2.5 min and had decreased to 96.7% after 16 min of heating due to the evaporation of moisture. In SHS+WMD heating, the relative mass of the potatoes increased in the early stage of heating, as with SHS heating. After 5 minutes of heating, the relative mass of the potatoes decreased, although the mass ratio decreased much more slowly than with SHS heating. Water droplets in SHS, which were sprayed on the surface of the potatoes, supplied moisture to the potatoes and prevented drying.

Figure 5 presents changes in the breaking stress of potato specimens in the blanching process. Breaking stress was measured using a creep meter (RE-35000, Yamaden, Tokyo) by penetrating the sliced sample (10 mm thickness) with a cylindrical plunger (φ: 2 mm) at 0.5 mm/s. The breaking stress of potato specimens decreased, or in other words, the potatoes became soft as the heating time became longer in the case of all heating media. In hot water heating, the breaking stress of the potatoes decreased considerably, and potato tissue became brittle. These notable changes in potato texture due to hot water heating were presumably caused by the absorption of water by potato tissue and the dissolution of solid components from the potatoes into the hot water. In contrast to hot water heating, the softening of potato tissue was prevented in SHS+WMD and SHS heating at almost the same level.

SHS+WMD enabled the moisture regulation of food materials during SHS heating. SHS+WMD simultaneously improved the quality and the yield of blanched potatoes. This effect of SHS+WMD was also observed in the heating of Japanese radish roots[34], carrots[35], broccoli[56], green soybeans[57], and aroids[58].

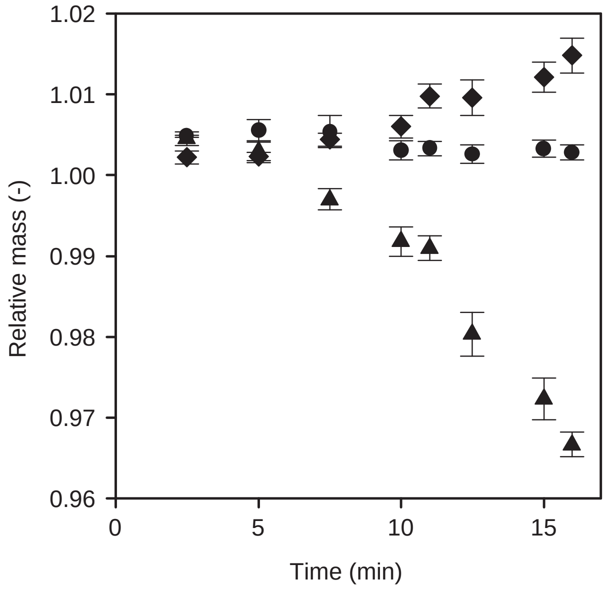

Fig. 4. Changes in mass of potato during heating process by SHS+WMD (●), SHS (▲), and hot water (◆)
Error bars represent standard error of the mean.

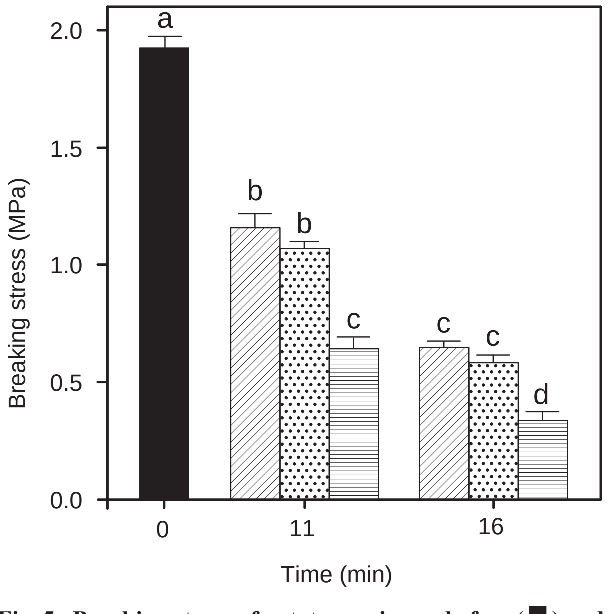

Fig. 5. Breaking stress of potato specimens before (█) and after heating with SHS+WMD (////), SHS (░), and hot water (≡)
Error bars represent standard error of the mean. Bars with the same letter are not significantly different. (Tukey's HSD, $P < 0.05$).

Surface pasteurization of cucumber fruit [44]

These days, the cut fruit and vegetable market as well as the market for ready-to-eat meals using fresh vegetables are increasing. Potato salad is one of the major ready-to-eat meals sold at supermarkets. Potato salad usually consists of boiled and mashed potato, mayonnaise, and some kinds of fresh vegetables, including cucumber fruit, onion, and cabbage. The shelf life of potato salad is relatively short as microorganisms from cucumber fruit rapidly proliferate inside mashed potato. On the surface of fresh cucumber fruit, the population of microorganisms is usually $10^7 \sim 10^8$ CFU/g. Hypochlorite solution enables the decontamination of 2 to 3 log CFU/g of microorganisms with slight flavor and texture changes; however, the decontamination effect remains unsatisfactory. Suppliers and distributors of ready-to-eat meals are currently looking for technology that will enable the effective decontamination of microorganisms from fruits and vegetables without significant changes in quality.

In many fresh fruits and vegetables, microorganisms inhabit only the surfaces. This suggested that brief, efficient heating will provide effective pasteurization for fresh fruits and vegetables without major changes in quality. This is because the higher heat transfer rate allows the surface temperature of the vegetables to be raised high enough for pasteurization before the heat conducts into the vegetables from the surface.

Although conventional SHS shows a high heat transfer rate due to latent heat, it was found that the heat transfer rate was enhanced by adding water micro droplets to SHS. Figure 6 presents changes in the difference between the core temperature of the potato cylinder and the final temperature of the potato cylinder (i.e. 100°C)[47]. In this experiment, potato cylinders with 8 mm diameter were heated with SHS+WMD and SHS. For SHS+WMD heating, the SHS and WMD flow rates were 2.46 and 0.54 kg/h respectively, while the flow rate was 3.0 kg/h for SHS heating. The temperature of SHS was 115°C in both cases. The decimal reduction time of the temperature difference T_f - T by SHS+WMD heating was shorter than by SHS heating, i.e., SHS+WMD presented a higher heat transfer rate. One reason that the heat transfer of SHS was enhanced by water droplets may be as follows: When SHS was used for heating, a layer of condensed water formed on the surface of the object, through which heat was transferred from SHS to the object. When micro droplets were sprayed with SHS, the water layer was stirred by the collisions of the droplets with the object, and the thermal resistance of the water layer presumably decreased. Thus, the heat transfer from SHS to the object was enhanced by the presence of WMD. It is expected that SHS+WMD enables efficient surface pasteurization of vegetables with slight changes in quality.

Figure 7 plots the decreases in the standard plate count of cucumber fruit bacteria in the heating processes. The cucumber fruit dissected in 10 ~ 15 mm were heated with SHS+WMD, SHS, and boiling hot water. In SHS+WMD and SHS heating, the steam temperature was controlled at 115°C. After heating, samples were cooled by ice water. The microorganisms on the samples were cultivated on standard plates for 48 h at 37°C, and the number of the colonies on the plates were counted. SHS+WMD heating exhibited the highest pasteurization effect among the three heating media. This was presumably because the surface temperature of the cucumber fruit increased fastest in SHS+WMD heating.

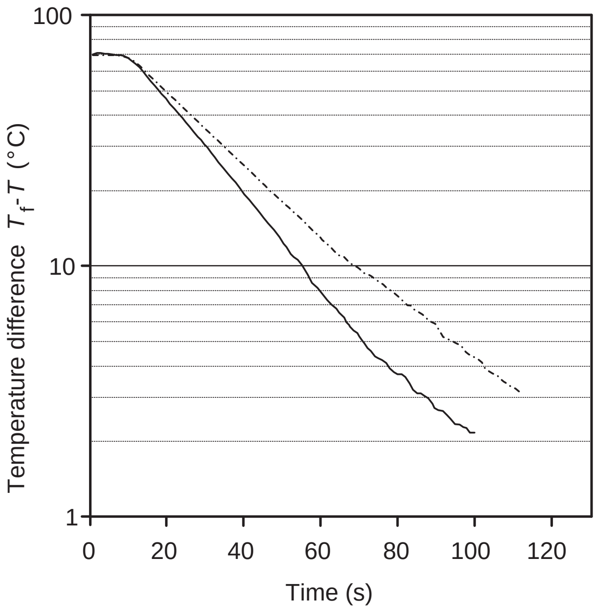

Fig. 6. Differences between the final temperatures of potato specimen T_f (100°C) and the core temperature of potato cylinder T

The potato cylinders were heated with SHS+WMD (⊠⊠) and SHS (– ⊠ – ⊠ –).

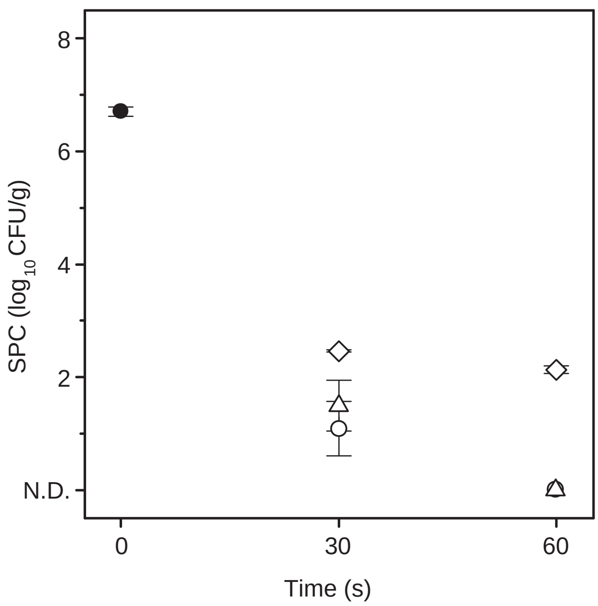

Fig. 7. Standard plate count of cucumber fruit bacteria

The cucumber fruit were raw (✧) or heated with SHS+WMD (✳), SHS (△), and hot water (★).

Figure 8 plots changes in the ratio of breaking stress and breaking strain of the cucumber fruit in each heating process. This ratio represents the crispness of the cucumber fruit. The breaking stress and the breaking strain were measured using a creep meter (RE-35000, Yamaden, Tokyo) by penetrating the sample with a cylindrical plunger (φ: 2 mm) from the epidermis at 0.5 mm/s. As the heating time increased, the cucumber fruit became soft and less crisp especially in hot water heating. In SHS+WMD heating for 30 s, the change in the cucumber fruit texture was relatively small. This was presumably because SHS+WMD heating did not induce water absorption or water loss in the cucumber fruit.

Practical applications of the SHS+WMD system

The SHS+WMD systems are currently used in food industries for cooking potato salad, boiled pork, and beef products[61], as well as for the surface pasteurization of dried fishery products. Potato salad is one of the major products in the home meal replacement (HMR) market in various regions around the world. SHS+WMD was found to prevent flavor loss in potato. The flavor of the potato salad was improved by the SHS+WMD system. Potato salad cooked with the SHS+WMD system has been sold at more than 100 supermarkets in Ibaraki, Chiba, Tochigi, and Saitama prefectures in Japan since 2005, and the amount of sales is 90,000 to 120,000 packs (100 g/pack) per month.

One of the other applications of the SHS+WMD system is cooking meals for patients who have undergone hematopoietic stem cell transplantation (HSCT) in the National Cancer Center Hospital in Tokyo, Japan. After HSCT, autoclaved meals are usually served to the patients since their immunogenic potential is extremely low. However, it has been pointed out that autoclaved meals lower the quality of life (QOL) of the patients since the autoclaving process limits variety in menus and causes flavor loss in the meals. To improve the QOL of HSCT patients, the National Cancer Center Hospital has started a trial where the SHS+WMD system is applied to cooking and processing meals for HSCT patients. In the trial, the autoclaved vegetables in the meals are replaced by vegetables steamed and pasteurized by the SHS+WMD system, which have a similar flavor and texture to fresh vegetables. The SHS+WMD system increases the variety and improves the quality of the meals for HSCT patients.

Conclusions

The SHS+WMD system was originally developed for heating agricultural products without moisture absorption, moisture loss, and component loss in the products. The SHS+WMD system is generally suitable for processes where product quality is affected by moisture absorption, moisture loss, and the loss of solid components. In addition, it was found that WMD increased the heat transfer rate of SHS. This effect is preferable for a heating process where the surface temperature of a product should increase rapidly, such as for the surface pasteurization of vegetables. In actual food processing, however, it is difficult to predict

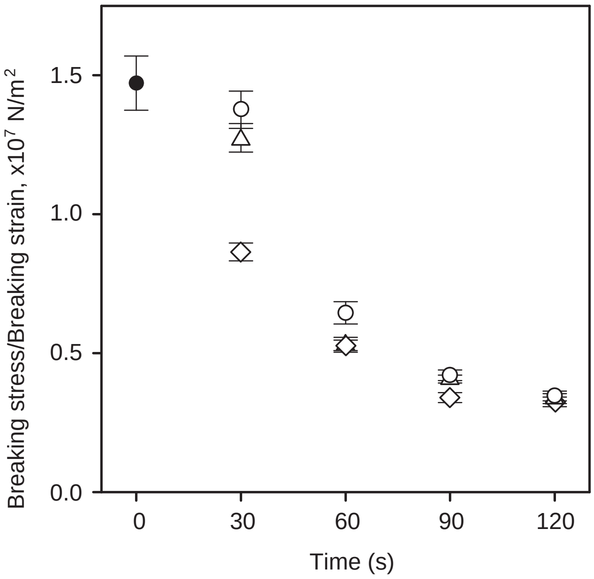

Fig. 8. Changes in the texture of cucumber fruit by heating process
The cucumber fruit were raw (✧) or heated with SHS+WMD (✡), SHS (△), and hot water (★).

which product or process the SHS+WMD system is suitable for, because the relationship between the changes in quality and moisture or temperature profiles of a product during processing is extremely complicated. In future studies, therefore, it is necessary to examine the system in terms of various kinds of products and processes to expand the application of the system.

Acknowledgments

This work was supported by the Research and Development Program for New Bio-industry Initiatives from the Bio-oriented Technology Research Advancement Institution.

References

1. Abe, T. & Miyashita, K. (2006) Surface sterilization of dried fishery products in superheated steam and hot air. *Nippon shokuhin kagaku kougaku kaishi* (*J. Jpn. Soc. Food Sci.*), **53**, 373–379 [In Japanese with English summary].
2. Abe, T. & Miyashita, K. (2007) Heat treatment of scallop adductor muscle using superheated steam. *J. Food Sci.*, **72**, E345–E350.
3. Amatsubo, T., Hagura, Y. & Suzuki, K. (2006) The effect of superheated steam treatment on the quality of vegetable oils. *Food Sci. Technol. Res.*, **12**, 114–118.
4. Barbieri, S., Elustondo, M. & Urbicain, M. (2004) Retention of aroma compounds in basil dried with low pressure superheated steam. *J. Food Eng.*, **65**, 109–115.
5. Burg, P. & Fraile, P. (1995) Vitamin C destruction during the cooking of a potato dish. *Lebensm. – Wiss. u. – Technol.*, **28**,

506–514.
6. Cenkowski, S. et al. (2007) Decontamination of food products with superheated steam. *J. Food Eng.*, **83**, 68–75.
7. Collier, C. P. & Townsend, C. T. (1956) The resistance of bacterial spores to superheated steam. *Food Technol.*, **10**, 477–481.
8. Elustondo, D., Elustondo, M. P. & Urbicain, M. J. (2001) Mathematical modeling of moisture evaporation from foodstuffs exposed to subatmospheric pressure superheated steam. *J. Food Eng.*, **49**, 15–24.
9. Fraile, P. & Burg, P. (1997) Reheating of a chilled dish of mashed potatoes in a superheated steam oven. *J. Food Eng.*, **33**, 57–80.
10. Fraile, P. & Burg, P. (1997) Influence of convection heat transfer on the reheating of a chilled ready-cooked dish in an experimental superheated steam cell. *J. Food Eng.*, **33**, 263–280.
11. Head, D. S. et al. (2008) Effects of superheated steam on *Geobacillus stearothermophilus* spore viability. *J. Appl. Microbiol.*, **104**, 1213–1220.
12. Hiranvarachat, B., Suvarnakuta, P. & Devahastin, S. (2008) Isomerisation kinetics and antioxidant activities of β-carotene in carrots undergoing different drying techniques and conditions. *Food Chem.*, **107**, 1538–1546.
13. Huang, T. C., Ho C. T. & Fu H. Y. (2004) Inhibition of lipid oxidation in pork bundles processing by superheated steam frying. *J. Agric. Food Chem.*, **52**, 2924–2928.
14. Iyota, H. et al. (2001) Drying of sliced raw potatoes in superheated steam and hot air. *Drying Technol.*, **19**, 1411–1424.
15. Iyota, H. et al, (2001) Simulation of superheated steam drying considering initial steam condensation. *Drying Technol.*, **19**, 1425–1440.
16. Iyota, H. et al. (2008) Effect of time-dependent humidity profiles from air to superheated steam on drying of a wetted starch sphere. *Drying Technol.*, **26**, 211–221.
17. Kingcam, R., Devahastin, S. & Chiewchan, N. (2008) Effect of starch retrogradation on texture of potato chips produced by low-pressure superheated steam drying. *J. Food Eng.*, **89**, 72–79.
18. Kondjoyan, A. & Portanguen, S. (2008) Prediction of surface and “under surface” temperature on poultry muscles and poultry skins subjected to jets of superheated steam. *Food Res. Int.*, **41**, 16–30.
19. Kondjoyan, A. & Portanguen, S. (2008) Effect of superheated steam on the inactivation of Listeria innocua surface-inoculated onto chicken skin. *J. Food Eng.*, **87**, 162–171.
20. Kozanoglu, B. et al. (2006) Drying of seeds in a superheated steam vacuum fluidized bed. *J. Food Eng.*, **75**, 383–387.
21. Kubota, K. et al. (1978) Soaking of superheated-steam-treated rice to prepare soaked rice of hi level moisture. *Nippon shokuhin kogyo gakkaishi (J. Food Sci. Technol.)*, **25**, 251–256 [In Japanese with English summary].
22. Lazar, M. E. (1972) Blanching and partial drying of foods with superheated steam. *J. Food Sci.*, **37**, 163–166.
23. Leeratanarak, N., Devahastin, S. & Chiewchan, N. (2006) Drying kinetics and quality of potato chips undergoing different drying techniques. *J. Food Eng.*, **77**, 635–643.
24. Léonard, A. et al. (2008) Effect of far-infrared radiation assisted drying on microstructure of banana slices: an illustrative use of X-ray microtomography in microstructural evaluation of a food product. *J. Food Eng.*, **85**, 154–162.
25. Marero, L. M. et al. (1986) Changes in the tocopherol and unsaturated fatty acid constituents of spices after pasteurization with superheated steam. *J. Nutr. Sci. Vitaminol.*, **32**, 131–136.
26. Markowski, M. et al. (2003) The effect of superheated-steam dehydration kinetics on textural properties of Asian noodles. *Trans. ASAE*, **46**, 389–395.
27. Methakhup, S., Chiewchan, N. & Devahastin, S. (2005) Effects of drying methods and conditions of drying kinetics and quality of Indian gooseberry flake. *LWT – Food Sci. Technol.*, **38**, 579–587.
28. Nathakaranakule, A., Kraiwanichkul, W. & Soponronnarit, S. (2007) Comparative study of different combined superheated-steam drying techniques for chicken meat. *J. Food Eng.*, **80**, 1023–1030.
29. Niamnuy, C., Devahastin, S. & Soponronnarit, S. (2007) Effects of process parameters on quality changes of shrimp during drying in a jet-spouted bed dryer. *J. Food Sci.*, **72**, E553–E563.
30. Nimmol, C. et al. (2007) Drying of banana slices using combined low-pressure superheated steam and far-infrared radiation. *J. Food Eng.*, **81**, 624–633.
31. Nishioka, F., Asaoka, D. & Ymazaki, M (2004) The research on the high quality of the boiled–dried adductor muscle (shiraboshi) using superheated steam. *Nippon shokuhin kagaku kougaku kaishi* (*J. Jpn. Soc. Food Sci.*), **51**, 167–171 [In Japanese with English summary].
32. Ono, K. et al. (2006) Sterilizing effect of superheated steam on microbes in Chinese cabbage. *Nippon shokuhin kagaku kougaku kaishi* (*J. Jpn. Soc. Food Sci.*), **53**, 172–178 [In Japanese with English summary].
33. Ono, K. et al. (2007) Effect of superheated steam treatment on the preservation and sensory characteristics of Buckwheat noodles. *Nippon shokuhin kagaku kougaku kaishi* (*J. Jpn. Soc. Food Sci.*), **54**, 320–325 [In Japanese with English summary].
34. Osada, S. et al. (2007) Basic cooking and processing properties of Aqua-gas treated food materials (Part 3) – Using root of Japanese radish –. *J. Integr. Stud. Diet. Habits*, **18**, 223–230 [In Japanese with English summary].
35. Osada, S. et al. (2008) Basic cooking and processing properties of Aqua-gas treated food materials (Part 5) – using carrot –. *J. Integr. Stud. Diet. Habits*, **19**, 239–246 [In Japanese with English summary].
36. Pimpaporn, P., Devahastin, S. & Chiewchan, N. (2007) Effects of combined pretreatments on drying kinetics and quality of potato chips undergoing low-pressure superheated steam drying. *J. Food Eng.*, **81**, 318–329.
37. Prachayawarakorn, S., Prachayawashin, P. & Soponronnarit, S. (2006) Heating process of soybean using hot-air and superheated-steam fluidized-bed dryers. *LWT – Food Sci. Technol.*, **39**, 770–778.
38. Pronyk, C., Cenkowski, S. & Abramson, D. (2006) Superheated steam reduction of deoxynivalenol in naturally contaminated wheat kernels. *Food Control*, **17**, 789–796.
39. Quast, D. G., Leitão, M. F. F. & Kato, K. (1977) Death of *Bacillus Stearothermophilus* 1518 spores on can covers exposed to superheated steam in a Dole aseptic canning system. *Lebensm. – Wiss. u. – Technol.*, **10**, 198–202.
40. Rordprapat, W. et al. (2005) Comparative study of fluidized bed paddy drying using hot air and superheated steam. *J. Food Eng.*, **71**, 28–36.
41. Rouatbi, M., Duquenoy, A. & Giampaoli, P. (2007) Extraction

of the essential oil of thyme and black pepper by superheated steam. *J. Food Eng.*, **78**, 708–714.
42. Smith, D. A. (1984) Peeled yield and quality of 'Delicious' apples peeled by superheated steam, saturated steam, and caustic peeling. *J. Amer. Soc. Hort. Sci.*, **109**, 364–367.
43. Soponronnarit, S. et al., (2006) Parboiling brown rice using super heated steam fluidization technique. *J. Food Eng.*, **75**, 423–432.
44. Sotome, I. et al. (2005) Sterilization of vegetables without deterioration in their quality by a combined treatment with superheated steam and hot water spray. *Bokin Bobai*, **33**, 523–530 [In Japanese with English summary].
45. Sotome, I. et al. (2005) Heat transfer and drying properties of superheated steam containing micro-droplets of water. *Jpn. J. Food Eng.*, **6**, 229–236 [In Japanese with English summary].
46. Sotome, I. et al. (2006) Blanching of potato with superheated steam containing micro-droplets of hot water. *Nippon shokuhin kagaku kougaku kaishi* (*J. Jpn. Soc. Food Sci.*), **53**, 451–458 [In Japanese with English summary].
47. Sotome, I. et al. (2009) Blanching of potato with superheated steam and hot water spray. *LWT – Food Sci. Technol.*, **42**, 1035–1040.
48. Sotome, I. et al. (2009) Measurement of steam/water ratio in the nozzle jet of an oven system using superheated steam and hot water spray. *Jpn. J. Food Eng.*, **10**, 163–173.
49. Taechapairoj, C. et al. (2003) Superheated steam fluidized bed paddy drying. *J. Food Eng.*, **58**, 67–73.
50. Taechapairoj, C., Prachayawarakorn, S. & Soponronnarit, S. (2006) Modelling of parboiled rice in superheated-steam fluidized bed. *J. Food Eng.*, **76**, 411–419.
51. Takenaka, M. et al. (2009) Changes in phenolic compounds during heating a potato. *Nippon shokuhin kagaku kougaku kaishi* (*J. Jpn. Soc. Food Sci.*), **56**, 171–176 [In Japanese with English summary].
52. Tang, Z., Cenkowski, S. & Muir, W. E. (2000) Dehydration of sugar-beet pulp in superheated steam and hot air. *Trans. ASAE*, **43**, 685–689.
53. Tang, Z. & Cenkowski, S. (2001) Equilibrium moisture content of spent grains in superheated steam under atmospheric pressure. *Trans. ASAE*, **44**, 1261–1264.
54. Tang, Z., Cenkowski, S. & Izydorczyk, M. (2005) Thin-layer drying of spent grains in superheated steam. *J. Food Eng.*, **67**, 457–465.
55. Tatemoto, Y. et al., (2001) Effects of operational conditions on drying characteristics in closed superheated steam drying. *Drying Technol.*, **19** 1287–1303.
56. Tonozuka, F. et al. (2005) Basic cooking and processing properties of Aqua-gas treated food materials – using broccoli –. *J. Integr. Stud. Diet. Habits*, **16**, 242–248 [In Japanese with English summary].
57. Tonozuka, F. et al. (2007) Basic cooking and processing properties of Aqua-gas treated food materials (Part 2) – About physical properties and the color by the heating method and the heating time of green soybeans –. *J. Integr. Stud. Diet. Habits*, **18**, 254–264 [In Japanese with English summary].
58. Tonozuka, F. et al. (2008) Basic cooking and processing properties of Aqua-gas treated food materials (Part 4) – using aroid. *J. Integr. Stud. Diet. Habits*, **19**, 214–223 [In Japanese with English summary].
59. Tsukada, N. (1984) Application of high pressure steam and superheated steam for food process. *Nippon shokuhin kogyo gakkaishi*, **31**, 536–545 [In Japanese].
60. van Loon, W. A. M. et al. (2005) Study of a new energy efficient process for French fries production. *Eur. Food Res. Technol.*, **221**, 779–786.
61. Yamanaka, S. et al. (2007) Estimation of the pasteurization effect of superheated steam containing micro-droplets of hot water and its application for processing and cooking food. *Bokin bobai*, **35**, 341–349 [In Japanese with English summary].
62. Zanoelo, E. F., Cardozo-Filho, L & Cardozo-Júnior, E. L. (2006) Superheated steam-drying of mate leaves and effect of drying conditions on the phenol content. *J. Food Process Eng.*, **29**, 253–268.